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Multi-Building Microgrids for a Distributed Energy Future in Portugal

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MULTI-BUILDING MICROGRIDS FOR A DISTRIBUTED ENERGY FUTURE IN PORTUGAL

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ABSTRACT

Within the research field of distributed generation, special attention has been lately drawn to the concept of microgrids, an alternative for realizing the potential of dispersed and localized supply of heat and power. A microgrid is a locally organized group of electricity generation, storage and loads that operate together in a grid-connected fashion, through a single point of common coupling and being able to work in stand-alone conditions if circumstances so dictate. Waste heat from generators can be ideally recovered to meet heating loads of the system.

Effective design of microgrid systems can be supported by optimization methods incorporating multi-building modeling capabilities. Previous work from the authors has suggested DER-CAM, which features a robust and flexible optimization algorithm, as a viable tool for exploring integrated energy microgrid systems' design modeling (Mendes et al., 2011).

This study looks at the potential penetration of multi-building integrated energy microgrids in the urban context. Its main objectives are: 1)To realize how differently would distinct building typologies adopt the microgrid concept; 2)To understand the patterns by which this adoption would take place; 3)To identify the added costs or benefits and GHG emissions at which adoption effectively occurs.

The research steps related to algorithm expansion to cope with multi-buildings microgrids modeling and to the adaptation of DER-CAM to the Portuguese case-study economic, environmental and technological setting are firstly explained. Essential load data as well as updated technology specifications have been collected by the authors from Portuguese energy services companies.

The research results presented suggest that if optimally designed, the microgrid form can provide economic and environmental improvements at a given site of four different studied typologies, adding to increases in the overall reliability. The latter is valued differently by each complex typology. Urban mixes of different typologies also have significant importance and represent benefits to the customers. The average economic benefit from microgrid adoption in the investigated cases was found to be of 20%. Scale economies from joint investments in microgrid capabilities can reach 10%, compared to separate investment by each one of the single typologies. Also, load complementarity is an important aspect to take into account. Moreover, economic gains can be enhanced if, through a point of common coupling, energy sales to the macrogrid operator take place. From the environmental point of view, average GHG emissions reduction was of 20%. Particularly, Health and Office complexes might find microgrid adoption exceptionally attractive. Such benefits through investments in DG, especially the economic ones, can constitute attractive field for entrance of ESCO businesses in the microgrid market.

The Portuguese technical-economic context and climate currently favor investments in solar energy technologies rather than on fuel-fired ICEs, FCs and MTs due to capital prices and increasing natural gas tariffs. Electrical battery storage has also considerable importance as a backup for energy management and reliability purposes. However, if investments in microgrid adoption become driven by environmental criteria, CHP DG as well as absorption cooling equipments might have an important role to play. The results for the case-study in Portugal suggest that multi-building microgrids might play a significant future role in providing building complexes with its energy needs.

Keywords: microgrids, distributed energy, optimization, multi-building complexes, Portuguese urban context.

1. INTRODUCTION

A paradigm change on current energy systems, instigated by new global economic, environmental and technological trends is taking place worldwide. The move towards the decentralization of energy supply and distribution, cleaner and widely more efficient, better managed energy systems is becoming increasingly acknowledged as part of future societies. In this context, distributed generation (DG) has been progressively introduced due to its potential to combine power and heat at the locus of consumption, with multiple benefits to the customers, the utility and the society as a whole, such as economic savings, environmental improvements, boost of markets competition and innovation, improved utility performance, increased power and engagement of the consumer.

The concept of having a considerable number of small-scale generation units dispersed and inter-connected over a grid has gained considerable interest from the scientific community in the last few years. Several research groups around the world are exploring pathways for development of the microgrid, known as an alternative approach for integrating small scale DG of approx. <1MW into low-voltage electricity distribution systems, which could lead the way in such a reform in the traditional energy system. Microgrids operate together in a grid-connected fashion through a single point of common coupling, being able to isolate if circumstances dictate.

Distributed energy technologies can be considered the fundamental units of microgrids. The authors have been working on the concept of Integrated Community Energy Systems (ICES). ICES are an extension of the microgrid concept. They are independent community-scale, multi building, multi typology systems that make use of the synergies between numerous customers and rely on the combination of a rich DG technology mix, including intermittent sources such as wind power, photovoltaics and solar thermal, small dispatchable sources such as Internal Combustion Engines (ICE), FC, MT and small gas engines (GE) backed up by energy storage technologies. ICES are grid-connected systems. Grid connection results in increased overall reliability and security through energy autonomy and intentional islanding. Additionally, there are potential economic benefits for communities by selling of electricity to the utility operator - the macrogrid.

Appropriate design of ICES must be aided by optimization methods and tools able to fully capture the integrated nature of these systems. Previous work from the authors (Mendes et al., 2011) has suggested DER-CAM (Stadler et al., 2010, 2009) as a viable tool for exploring integrated energy microgrid systems' design modeling. For instance, an important aspect of ICES is the consideration of environmental concerns in its planning and operation stages. Some authors (Allison and Lents, 2002, Greene and Hammerschlag, 2000) have alerted to potential global, regional and local impacts in the forthcoming scenarios of massive DG adoption. In these studies the potential of DG to reduce air pollution burdens is recognized. Still, technology forcing in the specific form of tighter regulation is advocated, towards the promotion and adoption of the Best Available Technologies (BAT) for ICES. In this work, the authors focus on the most well-known environmental problem, Global Warming, which is caused by three main pollutants: Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O). The contribution of each pollutant is given by its Global Warming Potential[4] (GWP).

Three main microgrid research regions exist worldwide, which have been studying the microgrid concept since its inception and explore its diverse areas of interest from modeling to real development case-studies. They are North America, the EU and Japan (Table 1). A few successful microgrid pilot projects exist worldwide; the USA leads.

Table 1 – Motivations for worldwide microgrid research.

Research driving forces	North America[1]	EU	Japan
Reliability of power supply	•		
Reduction of investments in plants and equipment	•		
Reduction of energy costs	•	•	
Reduction of environmental burdens		•	•
Diversity of energy supply	•		•
Supply to islands and other remote places		•	•

Different motivations drive microgrid research being conducted in each of these regions (see Table 1). In the EU, these investments are directed to cost and emissions abatement, since in Europe environmental agreements such as the Kyoto protocol are strategically very relevant.

In Portugal, there is an important tradition of microgrid research, mainly focused in solving electrical engineering technical issues of increasing DG capacity but very few studies exist related to microgrid economic or environmental design and planning. From the legal point of view, the minigeneration regime, applicable to small enterprises (cap<250kW) corresponds to an advance towards a distributed energy future however it is still very recent and exclusively designed for renewables. At the same time combined heat and power technologies have not been ideally promoted in the country.

This study looks at the potential penetration of multi-building integrated energy microgrids in the Portuguese urban context, for supplying a number of building complexes of different typologies with its power and heat needs. It explores multiple patterns of microgrid adoption by different building typologies or its combinations, to better understand what factors drive them and the answer to questions such as "*What are the average costs or benefits that result from microgrid adoption*?", "*Where do they occur?*" or "*Which technologies would a microgrid preferably use*?" is also a main goal. Ultimately, the authors intend to sustain future planning decisions for Portugal in the field of distributed energy systems.

[1] Microgrid R&D developments in North America have been taking place mainly in the USA and Canada.

2. METHODOLOGY

2.1 The Distributed Energy Resources Customer Adoption Model (DER-CAM)

Microgrid adoption is performed with the DER-CAM tool, an optimization program created by researchers from the Lawrence Berkeley National Laboratory (LBNL). DER-CAM finds the total cost and the greenhouse gases (GHG) emissions minimizing combination and operation profiles of a set of DG technologies that meet a building's heat and power loads over a typical year. The tool solves a mixed integer linear program (MILP) written in the General Algebraic Modeling System (GAMS[2]). DER-CAM objective functions, both to be minimized are expressed below, in equations 1 and 2 (Stadler et al., 2010, 2009):

Cost minimization[3]:

$$C_{total} = C_{DG} + C_{elec} + C_{fuel} - \sum_{m}\sum_{h} S_{m,h} \cdot \quad (1)$$

GHG emissions minimization[3]:

$$GHG_{total} = GHG_{elec} + GHG_{fuel} \quad (2)$$

in which

C_{total} is the total annual energy costs of the whole microgrid, in EUR,

C_{DG} is the total DG investment capital cost, including renewable energies and battery storage, in EUR,

C_{elec} is the total sum of electricity costs in EUR,

C_{fuel} is the total sum of costs with fuels in EUR,

$S_{m,h}$ is the electricity sales to the macrogrid in EUR,

m and h are to the month (1..12) and hour (1..24) equation indices,

GHG_{total} is the sum of the total annual GHG emissions associated to the system operation, in $kgCO_2eq$[4].

GHG_{elec} is the sum of the total annual GHG emissions derived solely from the purchase of electricity from the system, in $kgCO_2eq$.

GHG_{fuel} is the sum of the total annual GHG emissions resultant from fuel consumption operations, in $kgCO_2eq$.

The authors implement an integrated analysis of the GHG emissions along with the traditionally economic overview. This approach considers the balanced emissions from CO_2, CH_4 and N_2O to elaborate a GHG aggregate factor in CO_2eq. units[5].

2.1.1 Multi-building microgrid adoption with DER-CAM

The most important inputs to DER-CAM are the building energy load profiles, organized by end-uses (electricity-only, space-heating, cooling, hot water and natural gas-only). Currently, in DER-CAM, the calculations of total electrical and NG costs of the system C_{elec} and C_{fuel}, is done in part by introduction by the user of the fixed and variable tariffs for electricity and fuels. However, this works only for one building or building typology. In multi-building microgrid energy analysis often the user needs to deal with different energy cost structures, for instance in the cases of residential and commercial urban mixes. The authors expand this approach in DER-CAM to include effective multi-building typologies microgrid analysis. The total energy loads, electricity loads and fuel loads sums in kW, inputs to DER-CAM calculations are given according to the simplified mathematical description in equations 3, 4 and 5.

$$\sum_{i=1}^{n} Load_{i\in\aleph} = Load_1 + Load_2 + .. + Load_n \quad (3)$$

$$\sum_{i=1}^{n} ElLoad_{i\in\aleph} = \sum_{i=1}^{n} ElOnlyLoad_{i\in\aleph} + \\ + \sum_{i=1}^{n} CoolLoad_{i\in\aleph} + \sum_{i=1}^{n} RfLoad_{i\in\aleph} \quad (4)$$

$$\sum_{i=1}^{n} NGLoad_{i\in\aleph} = \sum_{i=1}^{n} SpaceHeatLoad_{i\in\aleph} + \\ + \sum_{i=1}^{n} WtHeatLoad_{i\in\aleph} + \sum_{i=1}^{n} NGOnlyLoad_{i\in\aleph} \quad (5)$$

where

$\sum_{i=1}^{n} Load_{i\in\aleph}$ is the sum of the n total loads of a multi-building microgrid, in kW,

$\sum_{i=1}^{n} ElLoad_{i\in\aleph}$ is the sum of the n total electrical loads of the microgrid, in kW,

$\sum_{i=1}^{n} ElOnlyLoad_{i\in\aleph}$ corresponds to the sum of the electricity-only loads of the whole microgrid, that is, loads that can only be met by electricity, such as lighting, all sorts of equipments, ventilation, in kW,

$\sum_{i=1}^{n} CoolLoad_{i\in\aleph}$ and $\sum_{i=1}^{n} RfLoad_{i\in\aleph}$ correspond to the sum of the cooling and refrigeration loads of microgrid, respectively, in kW,

$\sum_{i=1}^{n} NGLoad_{i\in\aleph}$ is the sum of the n total natural gas[6] (NG) loads of the microgrid, in kW,

[2]GAMS is a proprietary software product used for high-level modeling of mathematical programming problems. It is owned by the GAMS Development Corporation (http://www.gams.com) and is licensed to Instituto Superior Técnico.

[3]This formulation is simplified to present only its relevant components for this work, thus excluding other capabilities of DER-CAM such as electric vehicles and demand response consideration.

[4]For improved emissions analysis, the authors introduce in DER-CAM appropriately balanced composite GHG emission factors in CO_2 eq. units, which take into account emissions from the three most important GHG, CO_2, N_2O and CH_4. This is done through evaluation of global warming potential indexes for each emitting air pollutant.

[5]All of these three are important gases to analyze in distributed generation studies due to fuel combustion. GWPs: CO_2=1,CH_4 =21 , N_2O=310.

$\sum_{i=1}^{n} SpaceHeatLoad_{i\in\aleph}$ and $\sum_{i=1}^{n} WtHeatLoad_{i\in\aleph}$ correspond, respectively, to the sum of space heating and water heating loads of the microgrid, respectively, in kW,

$\sum_{i=1}^{n} NGOnlyLoad_{i\in\aleph}$ is the sum of the microgrid loads which are usually met by NG, such as cooking, in kW.

To perform the optimization with multiple building typologies DER-CAM sums up the different complementary loads to attain an aggregate single load profile; however, the building energy costs will be separately calculated, according to the structure of each tariff system. Numerous other functions of the model are implicated in this modification, but due to the applied character of this work the authors decided not to further detail the mathematical descriptions. Other vital inputs to DER-CAM are the current economic context that affects the site's purchase of energy, such as tariff structure and fuel costs or feed-in tariff details and DG technical, economic and environmental parameters, which will dictate the way the equipment satisfies the loads of the microgrid and the adoption decision.

DER-CAM allows for incorporating microgrid[7] capabilities in the modeling process. The tool models the reliability benefit of the microgrid, assuming that part of the loads at the site are critical and need to be provided in case of a macrogrid failure. The way in which customers value reliability heavily depends on the building typology. For instance, the importance of maintaining certain critical loads uninterruptable in a residential building is different than the one attributed to healthcare facilities. This affects considerably DG technology adoption, due to the fact that some equipment can provide the system with greater reliability. For example, PV is limited to daytime operation and cannot be used as backup during the night. Lead-acid batteries discharge is limited to 30% of rated capacity and they might not be fully charged when a grid failure occurs.

The reliability of ICEs and fuel cells is considered to be approximately 90%. Additionally, DER-CAM takes into account the availability of each installed technology for providing the critical loads onsite. In the particular case of PV and storage the availability is calculated based on the solar irradiation and charge/discharge cycles at a given site, according to equations 6, 7 and 8 (Stadler et al., 2009). If at any moment the power that the installed technologies provide does not meet the minimum required loads, DER-CAM suggests the purchase of supplementary DG.

$$AvSolarDay_m = \frac{\sum_{h\in H} SolarInsolation_{m,h}}{24}, \forall m \qquad (6)$$

$$AvSolar = \frac{\sum_{m\in M} AvSolarDay_m}{12} \qquad (7)$$

$$AvStorage = MaxDCR \cdot \frac{\left(24 - 1/ESMaxCR\right)}{24} \qquad (8)$$

being $MaxDCR$ and $ESMaxCR$ the electrical storage maximum charging and discharging rates.

A smart switch at the point of common coupling is needed to provide the interaction with the macrogrid and which seamlessly isolates the site during a grid disturbance. When the utility grid returns to normal, the microgrid automatically resynchronizes and reconnects. The switch is sized by DER-CAM to take the critical loads of the whole microgrid in event of a failure, according to equation 9.

$$\begin{aligned} Switchsize = \sum_{i=1}^{n} \big[& \min\{ElLoad_i\} \cdot BaseF_i + \\ & + \left(\max\{ElLoad_i\} - \min\{ElLoad_i\}\right) \cdot PeakF_i \big]_i \end{aligned} \qquad (9)$$

in which $i \in \aleph$ and

$BaseF_i$ corresponds to the fraction of electrical base load which is considered as critical load, in %,

$PeakF_i$ corresponds to the fraction of electrical peak load which is considered as critical load, in %.

The capital costs involved with the CERTS microgrid capabilities, e.g. the switch cost and others related with power electronics equipment are assumed by the user. Microgrid benefits added to a given site are expressed exclusively as monetary in DER-CAM.

2.1.2 Multiobjective optimization approach

DER-CAM supports a preference-based multiobjective approach, in which the economic objective $f_1(x)$ and the environmental objective $f_2(x)$ are typically combined in a weighted goal function. This is a rather simple and practical approach which nonetheless bears known issues of causing biases when searching for tradeoff solutions. In order to better explore the solution space (including non-convex regions) and to more effectively generate bi-objective Pareto frontiers, the authors introduce the necessary GAMS code changes to perform ε criterion-based multiobjective optimization. This method implies that single objective optimization is performed while the other objective is transformed into an additional constraint of the problem. The resulting multiobjective problem assumes the following form:

$$\begin{gathered} f_1(x),\ f_2(x) : A \to \Re \\ \min f_1(x) \mid x \in D \ s.t. \\ g_i(x) = 0 \mid i = 1..k\ ,\ h_j(x) \le 0 \mid j = 1..m \\ f_2(x) \le \varepsilon_n \mid n = 1..h \end{gathered} \qquad (10)$$

[6] The authors are considering only NG as a fuel for this work.

[7] Numerous microgrid philosophies exist in the literature. The concept adopted here is the one from the Consortium for Electric Reliability Technology Solutions (CERTS). For more info on the CERTS microgrid concept please refer to http://certs.lbl.gov/certs-der-micro.html

being $f_1(x)$ and $f_2(x)$ two objective functions defined from one set A to the real numbers, where $f_1(x)$ is to be minimized subject to the traditional constraints g and h, with k being the number of equality constraints and m the number of inequality constraints, but also becoming $f_2(x)$ itself a constraint to the problem, limited to the n[th] ε criterion value. The ε value is determined with initial DER-CAM runs where the upper and lower bonds of $f_1(x)$ and $f_2(x)$ are determined, a necessary condition to use this method. x is the decision variable in the feasible region $D \in \Re$.

Finally, one very important characteristic of DER-CAM is that the (economic) optimization is always performed from the customer adoption point of view. It does not optimize direct benefits for the utility or other third parties in this process. DER-CAM looks at reducing energy costs and at the financial attractiveness of investments on the customer perspective. Such a planning approach fits perfectly on current Momentum in Europe and particularly in the Portuguese economic context. Additionally, it might constitute attractive ground for ESCOs.

2.1.3 Technology specifications in DER-CAM

Table 2 to Table 4 describe the DG portfolio available in the DER-CAM runs as well as its technical and economic characteristics. Due to the fact that some of these equipments are subject to economies of scale, the technology options in DER-CAM are categorized as either discrete or continuous.

Table 2 - Technical and economic characteristics of available discrete technologies in DER-CAM (Goldstein et al., 2003).

	ICE		MT		FC	
	S	M	S	M	S	M
Capacity (kW)	60	250	60	150	100	250
Installed cost (€/kW)	2668	1625	2690	2191	4836	3875
Maint. cost (€/kWh)	0.013	0.010	0.011	0.011	0.022	0.022
Electrical Efficiency (%)	29	30	25	26	36	36
Heat to Power Ratio	1.73	1.48	1.80	1.40	1	1
Lifetime (years)	20	20	10	10	10	10

Notes: All technologies with CHP capabilities and running on NG. ICE - Internal Combustion Engine, MT - Microturbine, FC - Fuel Cell. S - Small sized equipment, M - Medium-sized equipment. Only-electricity technologies are considered as well in DER-CAM runs. Technology costs are rounded for presentation.

Discrete technologies are available to customers in limited units or sizes. Continuous technologies, on the other hand, are available in such a large variety of sizes that it can be assumed that capacity close to the optimal could be acquired. The turnkey cost regression analysis, for the Portuguese market context, of the continuous solar thermal technology (depicted in Table 3), is available in Figure 5.

Table 3 - Available continuous technologies in DER-CAM (Stadler, 2009 and own calculations).

	ES	TS	ST	PV
Fixed cost (€)	220	7452	1436	1294
Variable cost (€/kW or €/kWh for storage)	144	75	556	2293
Maintenance cost (€/kW or €/kWh for storage)	≈0	≈0	0,1	0,2
Lifetime (years)	5	17	20	20

Notes: ES - Electrical Storage (conventional Lead-Acid), TS - Thermal storage, ST - Solar thermal, PV – Photovoltaics, Abs – Absorption cooling. Technology costs are rounded for presentation.

Table 4 – Energy storage parameters considered in the DER-CAM (Stadler, 2009).

	ES	TS
Charging efficiency	0.9	0.9
Discharging efficiency	1	1
Decay	0.001[1]	0.01
Maximum charge rate	0.10	0.25
Maximum discharge rate	0.25	0.25
Minimum State of Charge	0.30	0

Notes: ES-Electrical storage (conventional Lead-Acid), TS - Thermal storage. All parameters are dimensionless. [1]The decay is relatively high due to the fact that lifetime of lead-acid batteries is assumed at its upper end, when the decay increases rapidly.

3. THE PORTUGUESE CASE-STUDY

One of the objectives of this work is to explore microgrid adoption patterns in the Portuguese urban context. For this to be achieved, a number of DER-CAM models were created that reflect the technological and environmental context as well as market conditions in the country. The different components which describe this adaptation can be detailed as: 1)Building load data gathering and organization in typical building profiles; 2)Environmental and technological data gathering and treatment; 3)Market data assessment. These steps are briefly explained in the next paragraphs.

3.1 Load data

Customer load data is the vital component for the analysis in this work, since it is the "signature" of the consumption patterns for each building typology. The present study is part of ongoing work on microgrid adoption for Portugal, for both residential and services buildings typologies.

3.1.1 Residential

Highly detailed residential load data[8] was provided to the authors under an agreement of collaboration with a Portuguese telemetry company. After careful data treatment, the authors were able to obtain, for a typical reference year, the electricity (Figure 1) and NG hourly load

[8] Residential metered data was provided to the authors with 5 minutes detail.

profiles for several different households in the continental Portuguese territory.

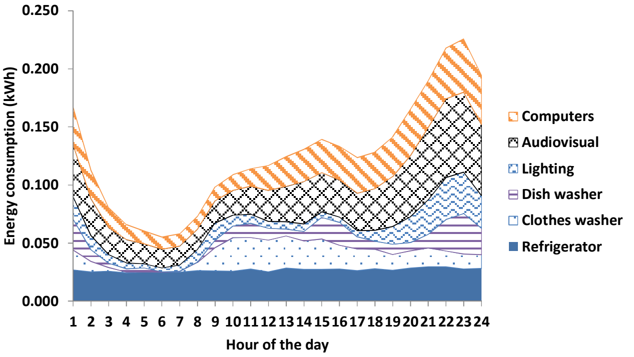

Figure 1 - Daily electricity-only (e.g. computing and lighting) consumption profile for the typical Portuguese family household.

Due to the relatively well characterized residential energy consumption in the Portuguese housing sector (EURECO, 2002 and DGEG, 2004) it was possible to generate the specific DER-CAM load profiles used in this work. A particular aspect of the energy consumption in households is that most part of electrical end-uses increase greatly by the end of the day trough night times, a cyclic pattern which as will be demonstrated, significantly affects DG adoption. For precision of results, residential data samples were adjusted by elimination of eventual outliers (<2% of occurrences) resultant from meter inaccuracies. DER-CAM final profiles for the specific end-uses were obtained through an excel macro load profile generator.

3.1.2 Services

Services buildings load data was obtained through collaborative research with a Portuguese energy services company. The authors acquired large volumes of information from services buildings energy audits. The data was obtained for multiple services buildings with various typologies and different sizes[9]. The energy analysis was constrained to four specific typologies: Education, Health, Lodging and Office buildings. The authors used the energy simulation software tool Visual DOE 4.1.2[10], to access each one of the specific building models and obtain the required hourly reports, inputs to DER-CAM. Specifically tailored building simulations in Visual DOE provided the authors with hourly reports for a reference typical year of: 1)Building space heating and cooling loads, in kW; 2)Interior and exterior lighting loads, in kW; 3)Equipment electrical loads, in kW; 4)Ventilation and pumping electrical loads, in kW; 5)Domestic hot water load, in kWh; 6) Total electric and NG loads, in kW. After the hourly reports output extraction from Visual DOE project files, the building simulation data was appropriately organized and consequently ranked by size, according to the electrical peak load for the reference year. This paper considers only medium-sized complexes, that is, with annual total electrical peak load between 100kW and 300kW.

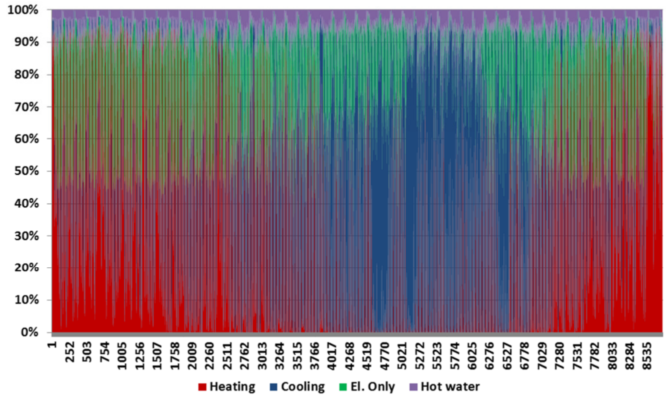

Figure 2 - TEC percent distribution in a typical Portuguese medium-sized education building complex.

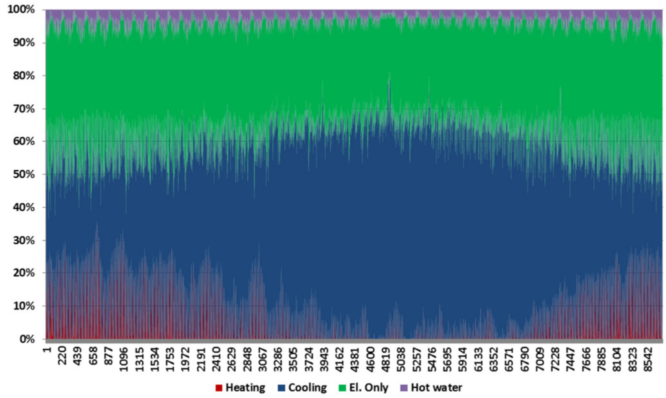

Figure 3 - TEC percent distribution in a typical Portuguese medium-sized office building complex.

Figure 2 and Figure 3 show the percent distribution of the total annual hourly energy consumption (TEC) in two typical Portuguese medium-sized services building complexes. One can notice that climatic dynamics in Portugal leads to much higher cooling consumptions compared to the heating ones, especially in services buildings, where normally internal heating loads assume great importance, reducing significantly the building heating needs. Such fact will most likely impact technology adoption. For instance for the lodging and health typologies the heating load is almost inexistent. Additional evidence that immediately comes out of these graphs is the heavy weight of electrical-only loads in the health and office typologies. In the cases of education and offices, there is also increased seasonal variability of the consumptions, while the remaining loads seem to be stable during the entire year. Service load data samples were as well adjusted, being eliminated the outliers with less than 2% of occurrences. Finally, DER-CAM 24h profiles for each month and by end-use were obtained through an excel macro load profile generator developed by DER-CAM team. Figure 4 describes the whole process of service buildings data management in a schematic view.

[9] Building sizes are estimated by using the total electrical peak load.

[10] Visual DOE is an advanced building energy simulation tool typically used in energy audit engineering or research services. It is owned by Architectural Energy Corporation. For more information please refer to http://www.archenergy.com/products/visualdoe

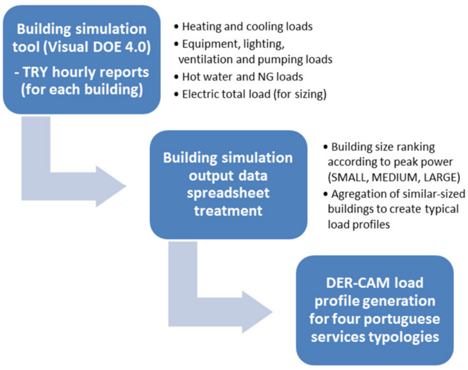

Figure 4 - Methodological sequence of services buildings load data treatment.

3.1.3 Technology data

The technology database was updated with cost data from the Portuguese market. Figure 5 shows the solar thermal cost curve, designed based on 85 different suppliers. The photovoltaics regression relies on data for 9 suppliers only; however a high R^2 (99%) provides the statistical confidence for using the resulting cost equation.

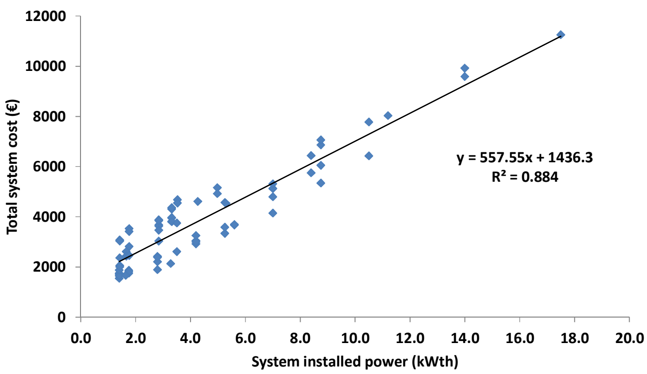

Figure 5 - Regression analysis of turnkey costs for solar thermal installations in the Portuguese market context.

3.1.4 Market data[11]

Table 5 presents the details of the electricity tariff considered in the DER-CAM runs for the Education, Lodging and Office typical Portuguese services buildings.

Table 5 - Details of the EDP electricity tariff "*MT – Médias utilizações em ciclo semanal normal*" for the Education, Lodging and Office typical Portuguese services buildings.

	Onpeaks	Midpeaks	Offpeaks	Super offpeaks
Volumetric charge (€/kWh)	Per. I, IV 0.125 Per. II, III 0.132	Per. I, IV 0.095 Per. II, III 0.095	Per. I, IV 0.059 Per. II, III 0.062	Per. I, IV 0.055 Per. II, III 0.058
Fixed charges (€/day)	423.53			
Demand charge (€/kW.month)	9.06			

[11] All prices presented in this section do not include additional taxes of 23% (considered in the runs).

Notes: Different volumetric charge values for the same time of day are related to the period of the year in which consumption occurs.

Due to its 24h operation schedule the health facility is instead served with the EDP electricity tariff "*MT – Longas utilizações em ciclo semanal normal*" with more attractive volumetric charges, from 0.054€/kWh, during off-peak periods, to 0.123€/kWh in the on-peak hours. It is assumed all residential microgrid customers have contracted the EDP electricity tariff "*BTN – Tarifa simples*" with a volumetric charge of 0.139€/kWh and daily fixed charges of 0.33€. Natural Gas is provided to a wide range of customers in Portugal by Galp Energia. Typical residential households can have it as set by the NG tariff "*Doméstico – Escalão 1*", for annual consumptions up to 200m^3 at a cost of 0.07€/kWh added to a fixed charge of 1.80€/month/household. For the services buildings served by by Galp Energia, the prices are set by the "*Pequeno terciário*" (Health and Lodging) and "*Grande terciário*" (Education and Office) NG tariffs. In both cases, the volumetric costs per kWh lower to 0.05.
The different building typologies have also different critical loads requirements in the event of a macrogrid failure then valuing differently the added reliability of the microgrid. These parameters for reliability benefits assessment with DER-CAM are presented in Table 6.

Table 6 - Reliability parameters for each one of the *building typologies.*

	BaseF	*PeakF*	Value (€)
RES	10%	5%	150
EDUC	25%	5%	200
HLTH	70%	10%	500
LODG	25%	5%	200

Notes: BaseF - percent fraction of electrical base load which is considered as critical load, PeakF - percent fraction of electrical peak load which is considered as critical load. The added microgrid value is estimated from previous work (Stadler et al., 2009).

From previous market studies from the DER-CAM team (Stadler et al., 2009), the cost of a fast seamless switch is considered to be of approximately 75€/kW plus an additional 20€/kW of DG which needs to be reformed in terms of electronic devices.

4. RESULTS AND DISCUSSION

Table 7 shows the result matrix from 28 cost minimizing optimization runs. The runs have included all the five above mentioned typologies, Residential, Educational, Health, Lodging and Offices. For ease of presentation, in this section, each one of these will be, from this point on, identified by the acronyms used in the result matrix (RES, EDUC, HLTH, LODG and OFF). All runs in Table 7 comprehend effective adoption of microgrid capabilities, which means every complex site has purchased a fast static switch which will seamlessly isolate the system from the main grid if a breakdown occurs. Taking into account the reliability parameters defined in Table 6, switch sizes vary from 16kW, purchased by the RES neighborhood, to over 100kW, in the highly demanding HLTH+OFF multi-building complex. None of the dual-typologies microgrids has purchased switch capacities under the 36kW (RES+LODG case).

Table 7 - Result matrix for the cost minimization investment analysis with DER-CAM. For each case, the upper area shows the Base Case run total annual energy cost (TEC) and GHG emissions. The lower area refers to the minimize cost run (minCost), with indication of the percent change in relation to the initial setting ("c. to BC" stands for "compared to the Base Case").

	RES	LODG	EDUC	HLTH	OFF
RES	***BC 148689€ 195344 kgCO$_2$eq.*** *minCost* *-7% c. to BC* 138727€ *-24% c. to BC* 149012 *kgCO$_2$eq.*	***BC 396252€ 704888 kgCO$_2$eq.*** *minCost* *-15% c. to BC* 335023€ *-33% c. to BC* 470946 *kgCO$_2$eq.*	***BC 409376€ 732474 kgCO$_2$eq.*** *minCost* *-18% c. to BC* 337556€ *-35% c. to BC* 476086 *kgCO$_2$eq.*	***BC 440002€ 775016 kgCO$_2$eq.*** *minCost* *-19% c. to BC* 355935€ *-36% c. to BC* 493558 *kgCO$_2$eq.*	***BC 491636€ 821451 kgCO$_2$eq.*** *minCost* *-20% c. to BC* 391028€ *-30% c. to BC* 572476 *kgCO$_2$eq.*
LODG		***BC 277999€ 509544 kgCO2eq.*** *minCost* *-19% c. to BC* 225528€ *-34% c. to BC* 335690 *kgCO$_2$eq.*	***BC 622173€ 1116802 kgCO2eq.*** *minCost* *-20% c. to BC* 500474€ *-32% c. to BC* 764013 *kgCO$_2$eq.*	***BC 601158€ 1089217 kgCO2eq.*** *minCost* *-22% c. to BC* 469959€ *-41% c. to BC* 637243 *kgCO$_2$eq.*	***BC 652169€ 1135652 kgCO2eq.*** *minCost* *-21% c. to BC* 512823€ *-30% c. to BC* 791364 *kgCO$_2$eq.*
EDUC			***BC 292698€ 537130 kgCO$_2$eq.*** *minCost* *-20% c. to BC* 234365€ *-34% c. to BC* 355818 *kgCO$_2$eq.*	***BC 617149€ 748022 kgCO$_2$eq.*** *minCost* *-23% c. to BC* 474116€ *-20% c. to BC* 601530 *kgCO$_2$eq.*	***BC 666498€ 1163237 kgCO$_2$eq.*** *minCost* *-22% c. to BC* 521203€ *-30% c. to BC* 810476 *kgCO$_2$eq.*
HLTH				***BC 323505€ 579672 kgCO$_2$eq.*** *minCost* *-24% c. to BC* 246347€ *-43% c. to BC* 328829 *kgCO$_2$eq.*	***BC 698166€ 1205780 kgCO$_2$eq.*** *minCost* *-24% c. to BC* 534074€ *-44% c. to BC* 677508 *kgCO$_2$eq.*
OFF					***BC 370267€ 626108 kgCO$_2$eq.*** *minCost* *-23% c. to BC* 283796€ *-27% c. to BC* 454731 *kgCO$_2$eq.*

Notes: RES - Residential typology, LODG - Lodging typology, EDUC - Education typology, HLTH - Health typology, OFF - Office typology, BC - Base Case, minCost: minimize total energy annualized costs run (TEC). Please note that all results include microgrid capabilities, such as invest in fast switch for satisfying critical loads of the complex if macrogrid breakdown occurs.

4.1 Benefits from microgrid adoption

One initial, very important deduction from Table 7 is that all typologies and complexes have benefited from switching to microgrid system, whether it is in economic or environmental terms. This means every single studied Portuguese complex typology could potentially reduce costs and GHG emissions if adopting the ICES - multi-building microgrid concept. The most modest Total Energy Cost (TEC) reduction occurs in the sole RES case (only 7%).

Remaining cases are all over 15% TEC reduction with an average of 20% for the whole tested sample. Particularly, the best relative TEC reductions are achieved with the typologies HLTH and OFF, both for sole and complex typologies. This might be related with the fact that these typologies are the ones that most benefit from added power quality and reliability from microgrid operation.

GHG emissions reductions achieved by microgrid adoption are of an average of 30% in the total cases. This relates especially to the high trend for adoption of solar-enabled technologies. In particular, aggregate loads with high electricity-only consumptions, such as the HLTH ones, have the potential to reach also high GHG emissions reductions.

Overall the relatively low heating loads have prevented great investments in CHP technologies, whose adoption is rather conditioned by minimum heating loads. The warm Portuguese climate leads to high cooling consumptions in service buildings, in opposition to the low heating ones. Additionally, in these cases, normally internal heating loads assume increased importance and reduce significantly the building needs for heat. For the same reasons the entirety of the cases invested in solar thermal heating, which is a way to provide heat to a complex at daily hours and during most times of the year, by using a cheap, mature technology and without any added tariff costs.

More surprising is a considerable tendency for PV adoption, when this technology is commonly featured as a second distributed option, especially compared to the ICE, due to capital costs, low efficiency and availabilities. All optimization runs have resulted in investment in PV technology, even when very demanding reliabilities are at stake, such as the cases of HEALTH and OFF. Very often substantial amounts of PV power are adopted that will satisfy not only the daily electrical loads (usually the whole sum) but also battery charging for peak curtailment during high energy cost hours. The authors consider that at least three factors have affected the substantial adoption of PV in building complexes: 1)Increasing rates of natural gas in Portugal, especially for services buildings, preventing greater investments in gas-fired discrete technologies; 2)Current lower market prices for PV systems; 3)High levels of solar irradiation during a great part of the year in Portugal. In some extent, the adoption patterns are in fact similar for most building complexes. The results for different complex typologies differ mostly on the amount of purchased power of the selected technologies. ES, ST, PV.

4.2 Scale economies

One of the major reasons for companies or customers to invest in microgrid technology would be the expected scale economies from joint adoption of DG. When systems get bigger, potentially the operational costs go down. The results from Table 7 show this is not always true, however for most of the cases, economies of scale do occur. See, for instance the resulting scale economies[12] from adoption of a community microgrid by a complex RES+EDUC, of almost 10% (36k€) or the one observed with RES+HEALTH of circa 8% (29k€). In fact, RES typology finds beneficial economies from joint investments in microgrid capabilities with all the other building typologies (LODG, of 8% and OFF of 7%). One of the reasons for this is that there is a significant drop in the daily consumption pattern of RES, which other typologies may explore for their own needs. RES in the other hand suffers from great differential in consumption during peak night hours, which is better manageable if there is a "partner" investing in generation capacity.

4.3 Load complementarity

One important remark to make from the result matrix in Table 7 is the subject of load complementary. From the complementarity point of view, the authors consider three types of loads: *Mostly daily* (EDUC and OFF), *Mostly nightly* (RES) and *Stable* (HLTH, LODG). The results show that, as expected, when microgrid adoption investments take place, the aggregation of complementary loads is economically beneficial. Consider, for instance, the above referred resulting scale economies of 10 and 8% from RES+EDUC and RES+HEALTH microgrid adoption. Both investments correspond to a peak curtailment exercise, where stabilization of the total load takes place. In the first case, load complementarity is greater and economic benefits are relatively higher, since both loads behave in an opposite way. The second example includes an already highly stable load, HLTH, and in this case the load balancing is slightly lower, but still important and providing economic gains. However, in a third case, the microgrid adoption by an EDUC+OFF complex did not generate any benefits (a loss of less than 1%). This happens due to the fact that two *Mostly daily* loads are faced with the problem of investing in DG which will supply large amounts of power to be used mainly during the day, creating capacity surplus and added costs. When demand decays, part of the capacity is left shutdown or additional storage is put into operation to collect energy to be used in the day after, creating a gap which will lead to higher costs. A similar situation is seen with HLTH+OFF or LODG+HLTH (a loss and a benefit of less than 1%, respectively) again because hypothetically no significant load complementarity occurs. This mismatching between supply and demand has been one of the fundamental problems in energy and a hurdle in the traditional macrogrid for decades. The results show that the adequate design of DG systems, particularly of integrated energy microgrids must as well incorporate this notion, for attainment of better planning practices.

[12] To calculate the scale economy, the min cost solution for the complex is subtracted from the sum of min cost solutions for each typology.

4.4 Electricity sales

A scenario of electricity sales to the macrogrid operator, through adoption of the Portuguese minigeneration regime, was tested. This legal framework allows for selling electricity with currently attractive feed-in tariffs which can reach 0.25€/kWh. For these runs the authors have used a balanced tariff of 0.15€/kWh. The tested typology complexes were RES+LODG, HLTH+OFF and EDUC+HLTH. Invariably, the microgrids have accomplished to sell electricity by purchasing additional PV modules. Sales to the grid occur by usage of excess PV capacity during daytime hours. Particularly, the EDUC+HLTH complex, was able to generate annual revenues, compared to the minCost solution, of over 20k€. Table 8 shows the results.

Table 8 – Electricity sales results.

Typology	Base case (BC)	minCost	minCost w/ sales	Percent reduction
RES+LODG	396252	335023	323728	-3.37%
HLTH+OFF	698166	534074	521283	-2.40%
EDUC+HLTH	617149	474116	450523	-4.98%

4.5 Multiobjective analysis

A multiobjective approach (see section 2.1.2) is used, considering the minimization of both costs and GHG emissions. Every optimization run in the multiobjective frontier is a tradeoff between the cost and environmental functions, considering all possible DG technologies in the optimization. Typically in DG investment problems, a greater focus on reducing emissions means the annual energy costs might increase. For exploring multi-criteria investment possibilities the authors have selected the RES+EDUC case. Figure 6 shows the Pareto multiobjective curve which has resulted from this analysis. The starting point of the multiobjective frontier is the Do Nothing (BC) case. In the multiobjective runs there is a relaxation of the problem with the exception of the available area for solar which is a physical characteristic of the system[13].

In Figure 6, S1 is the least expensive option to consider at the site (Pure cost solution). S1 belongs to a group of best compromise solutions, where extensive GHG emissions reductions are achieved through relatively low investments in microgrid adoption. S2 (the Full GHG option) is a highly expensive alternative, but where added to PV and ST, CHP FC and absorption cooling units are purchased and greater emissions reduction is achieved. This indicates that the adoption of gas-fired CHP technologies might increase in the case the area for solar is more constrained. If a customer wishes to invest, it is also useful to know that the best attainable compromises for this curve involve annual costs of circa 400k€, being attainable reasonable GHG emissions reductions with relatively small investments. Zero levels of GHG emissions are never reached for the studied case because for instance no actions on passive measures are considered.

[13] Education, lodging and offices - 2500m^2, health facilities - 5000m^2, residential neighborhood - 1000m^2.

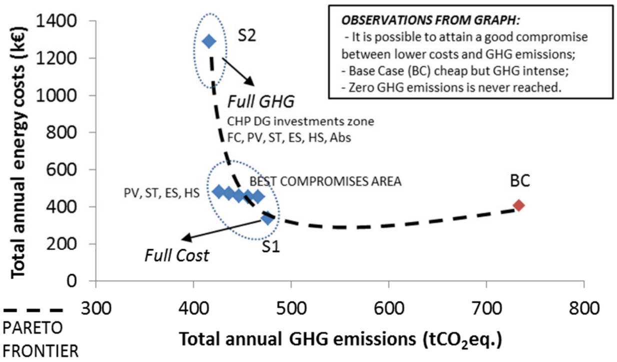

Figure 6 - Pareto frontier of the investment in microgrid adoption for the RES+EDUC case.

5. CONCLUSIONS

This study is part of ongoing work that looks at the potential penetration of multi-building integrated energy microgrids in the urban context for supplying a number of building complexes of diverse typologies with its power and heat needs. The authors look at the big picture of integrated energy microgrids penetration in the market and technical contexts, and not specifically at the single system level.

The results suggest that any of the studied typologies can find value in adopting DG in forms of small scale microgrids. This can happen within one single typology or in a context of combination between them. Average economic benefit from microgrid adoption is of 20%, compared to the Base Case. Scale economies from joint investments in microgrid capabilities can reach 10%, compared to separate investment by each of the single typologies. Load complementarity is very important for this aspect, being that adequate planning of integrated energy microgrids calls for adequate incorporation of this concept. From the environmental point of view, average GHG emissions reduction is of 20%. Particularly, Health and Office complexes might find microgrid adoption exceptionally attractive, from both the economic and environmental point of view. If under a context of attractive legal environment and feed-in tariffs, electricity sales to a macrogrid operator can still add economic gains to the equation. Such economic benefits through investments in DG might constitute attractive field for entrance of ESCO businesses in the microgrid market.

The current Portuguese technical-economic context, added to specific climatic conditions, seems to currently favor investments in solar energy technologies for both electricity and heat provision of building complexes, rather than on fuel-fired ICEs, FCs and MTs due to its high prices and natural gas prices. In the case of electricity, battery storage has also considerable importance as a backup for energy management and reliability purposes. However, if investments in microgrid adoption become driven by environmental criteria, CHP DG as well as absorption cooling technologies have an important role to play. It is seen that the adoption patterns do not differ much when looking at distinct building complexes, differing the results normally on the amount of installed power of the typically preferred technologies: ES, ST, and PV due to their lower prices in this study. Average investments in reforming a given medium-sized multi-building complex with microgrid capabilities can come around 400k€. This applies especially to Residential-Educational and Lodging-Office complexes. Fast switch capacities, to support the critical loads of the systems range somewhere between 40kW to 100kW.

It is seen that integrated community energy systems in forms of small-scale multi-building microgrids can play a major role in a forthcoming distributed energy future in Portugal. Further studies shall test this hypothesis and explore other features from ICES.

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